

Nuclear Physics Uncertainties in the Reactor Antineutrino Spectrum

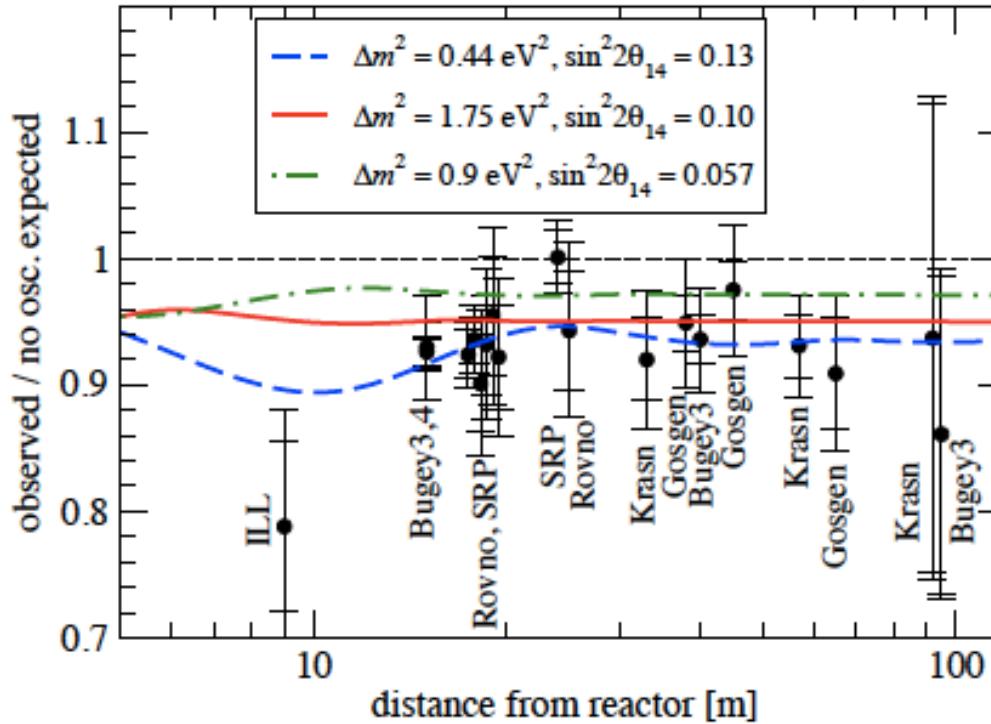
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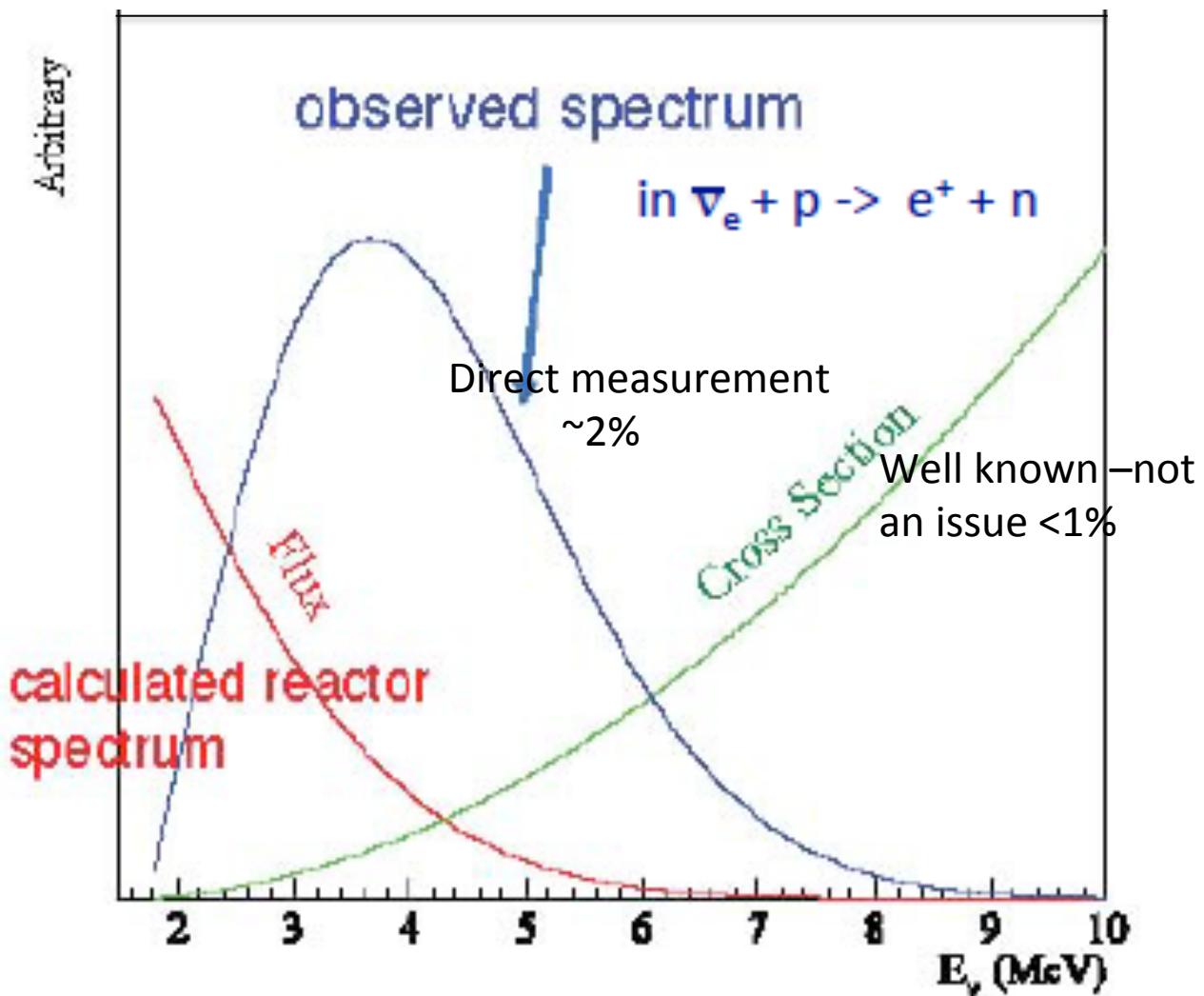
The Reactor Antineutrino Anomaly

$\text{obs/expected} = 0.936$ ($\sim 3\sigma$) deficit in the detected antineutrinos from short baseline reactor experiments

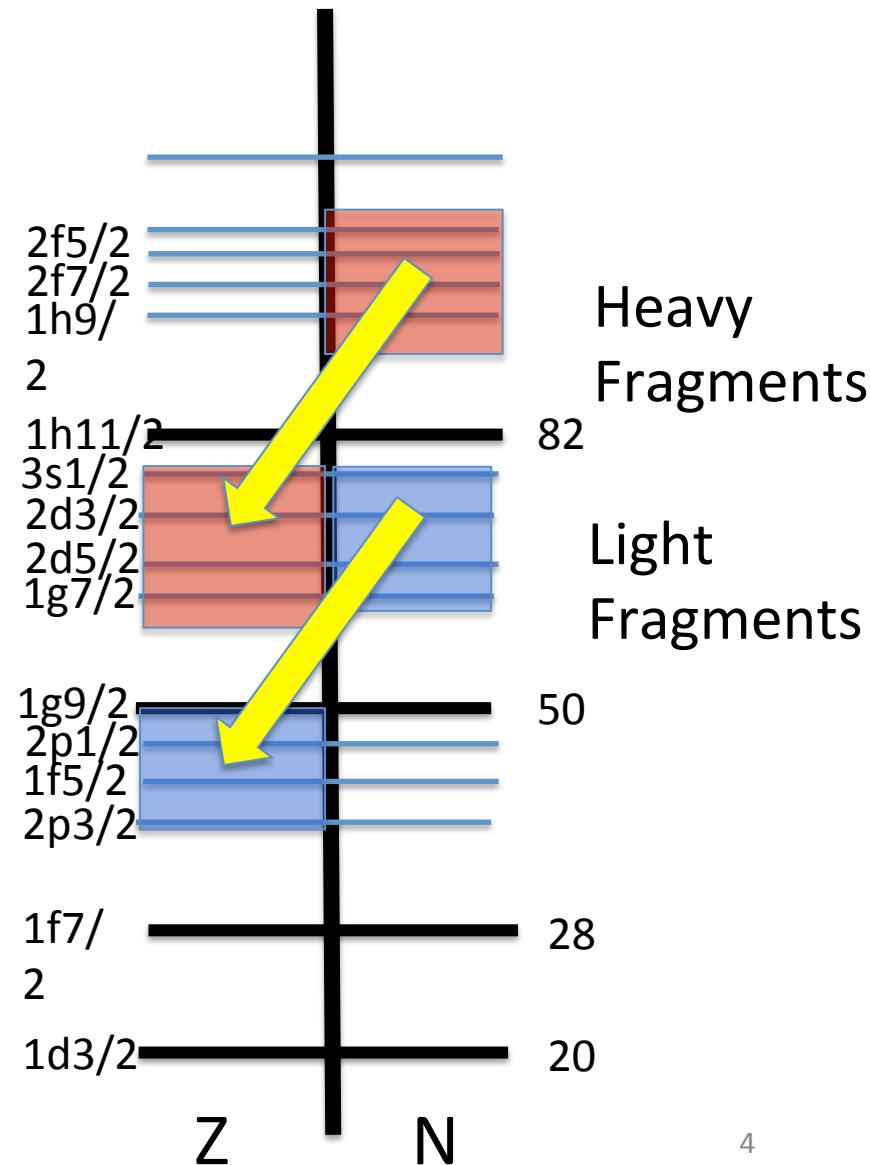
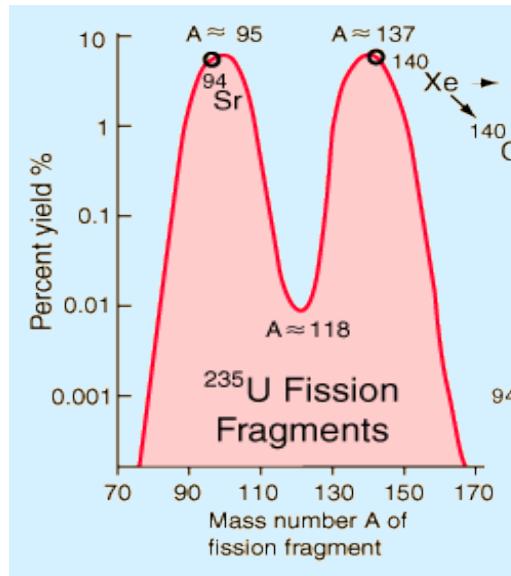


G. Mention, et al., Phys. Rev. D 83 073006 (2011); Th. A. Mueller, et al., Phys. Rev. C 83, 054615 (2011)
P. Huber, Phys. Rev. C 84, 024617 (2011); A. Hayes, et al, Phys. Rev Lett. 112, 202501 (2014)

The effect mostly comes from the detailed nuclear physics involved in the nuclear beta-decay of the fission fragments



Beta-decay of fission fragments produce antineutrinos at a rate of $\sim 10^{20}$ n/sec for a 1 GW reactor



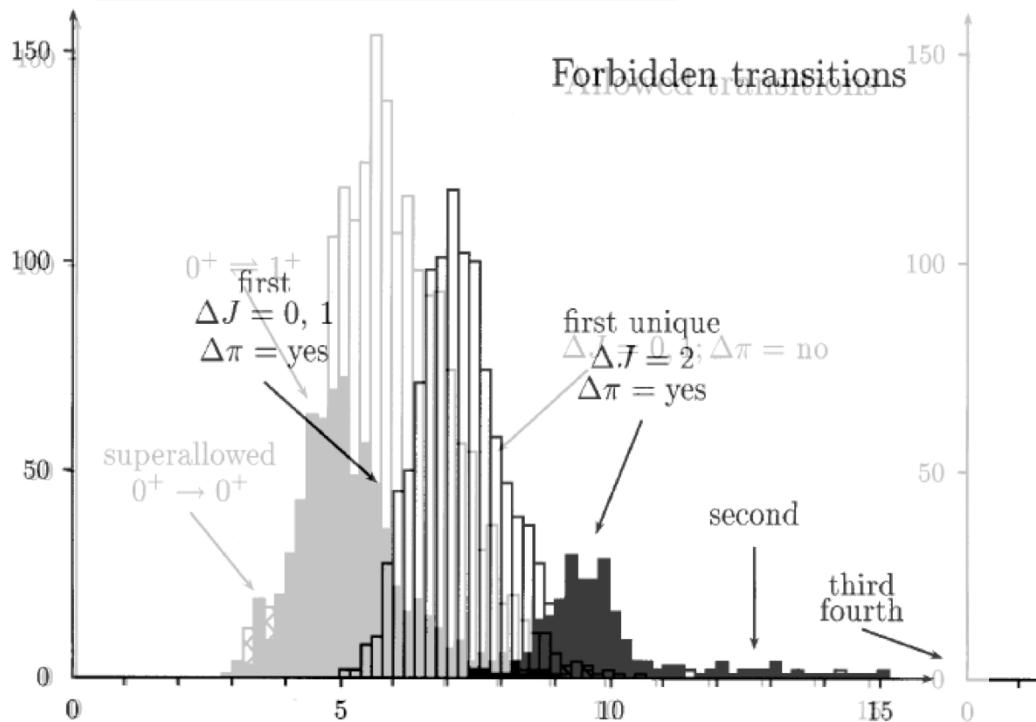
- Hundreds of fission fragments – all neutron rich
- Most fragments β -decay with several branches
- Approximately $6\nu_e$ per fission
- Aggregate spectrum made up of about six thousand end-points
- **About 1500 of these transitions are so-called forbidden transitions**

Log ft values – latest review

Nuclear Data Sheets 84, 487 (1998)
Article No. DS980015

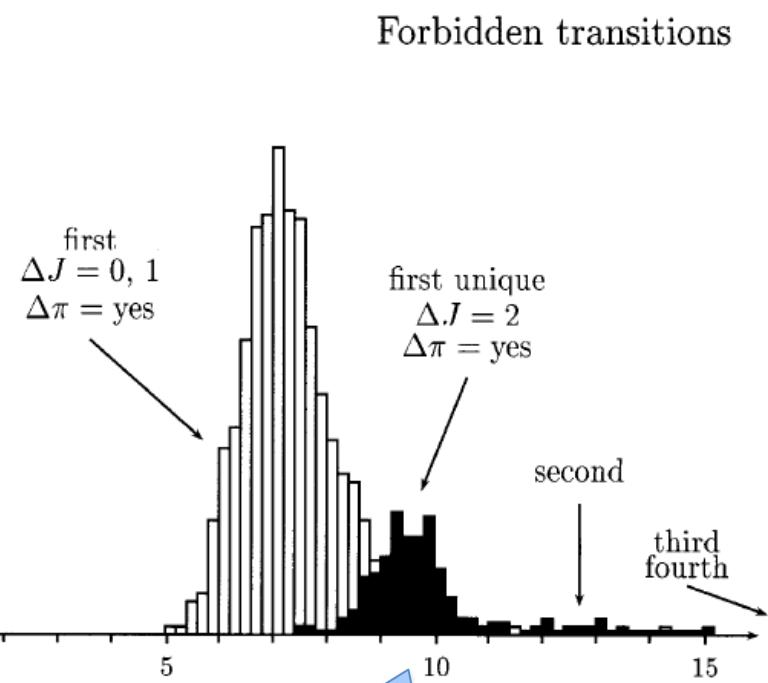
~3900 cases -> gives
centroids and widths

$$ft = \frac{6140}{\langle \vec{\tau} \rangle^2 + G_A^2 \langle \vec{\sigma} \vec{\tau} \rangle^2}$$

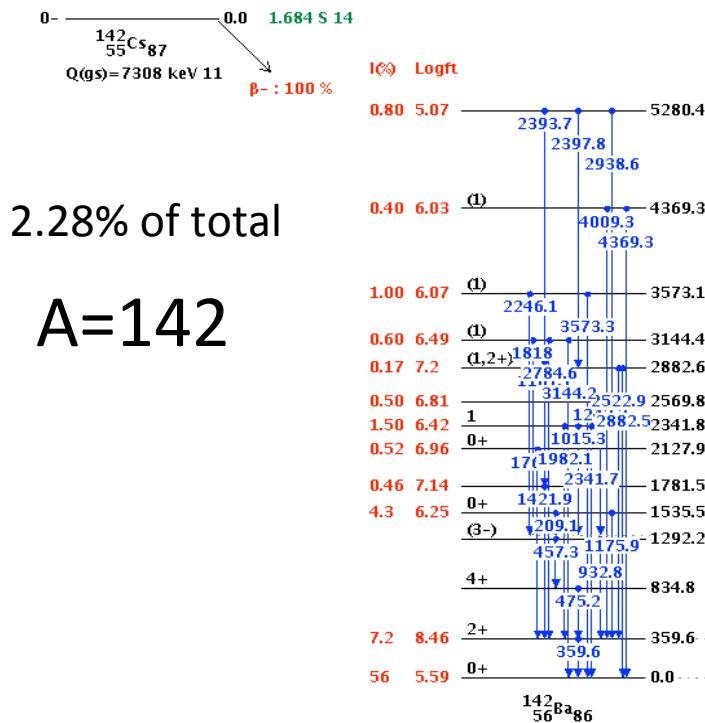


axial decay of free neutron
Log ft = 3.2

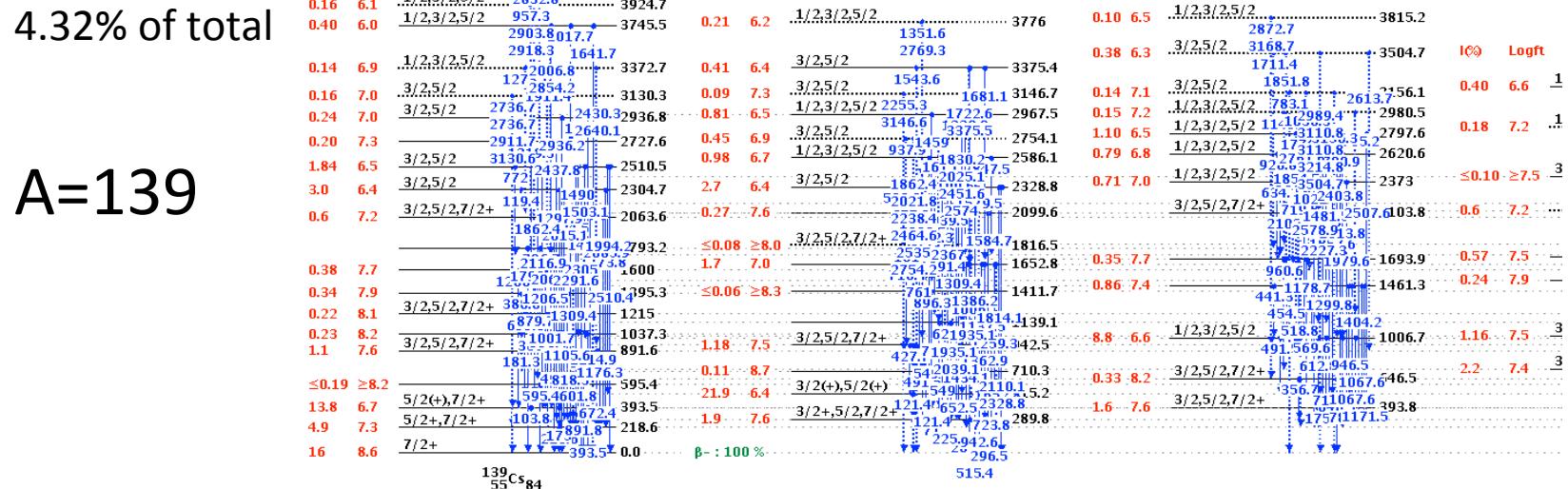
Log ft



used by previous authors as
characteristic of FF transitions

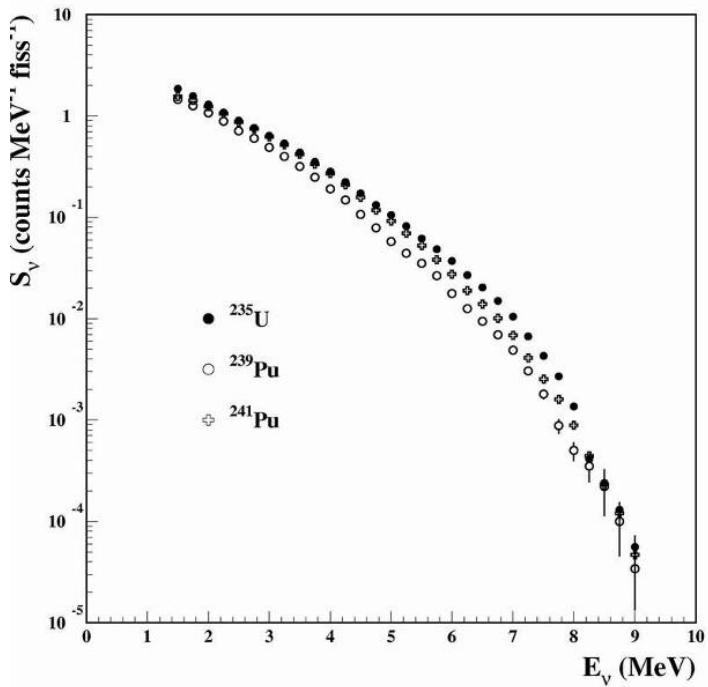


4.32% of total



Important beta decays should be large fraction of the total and should be energetic.

The antineutrino flux used in oscillations experiments is from a conversion of the aggregate beta spectra from ILL



F. von Feilitzsch et al. PLB118, 162 (1982)

A.A. Hahn et al. PLB160, 325 (1989)

P. Vogel et al., PRC 24 1543 (1981)

- Measurements at ILL of thermal fission beta spectra for ^{235}U , ^{239}Pu , ^{241}Pu
- Converted to antineutrino spectra by fitting to 30 end-point energies
- Use Vogel *et al.* ENDF estimate for ^{238}U
 $^{238}\text{U} \sim 7\text{-}8\%$ of fissions => small error
- All transitions were treated as allowed GT
- An approximate treatment was added for finite size and weak magnetism corrections

FIT

$$S_\beta(E) = \sum_{i=1,30} a_i S^i(E, E_o^i)$$

$$S^i(E, E_o^i) = E_\beta p_\beta (E_o^i - E_\beta)^2 F(E, Z)(1 + \delta_{RAD})$$

Known corrections to β -decay are the main source of the anomaly

$$S(E_e, Z, A) = \frac{G_F^2}{2\pi^3} p_e E_e (E_0 - E_e)^2 C(E) F(E_e, Z, A) \underline{(1 + \delta(E_e, Z, A))}$$

Fractional corrections to the individual beta decay spectra:

$$\delta(E_e, Z, A) = \delta_{rad} + \delta_{FS} + \delta_{WM}$$

- {
- δ_{rad} = Radiative correction (used formalism of Sirlin)
 - δ_{FS} = Finite size correction to Fermi function
 - δ_{WM} = Weak magnetism

Originally approximated as:

$$\delta_{FS} + \delta_{WM} = 0.0065(E_\nu - 4 \text{ MeV})$$



The difference between this original treatment and an improved treatment of these corrections is the main source of the anomaly

The finite nuclear size correction

Normal (point-like) Fermi function:

Attractive Coulomb Interaction increases electron density at the nucleus
=> beta-decay rate increases (effect largest for low energy electrons)

Finite size of Nucleus:

Decreases electron density at nucleus (relative to point nucleus Fermi function)
=> Beta decay rate decreases

Two contributions: nuclear charge density $\rho_{ch}(r)$ and nuclear weak transition density $\rho_w(r)$

For Allowed GT transitions:

$$\delta_{FS} = -\frac{3Z\alpha}{2\hbar c} \langle r \rangle_{(2)} \left(E_e - \frac{E_v}{27} + \frac{m^2 c^4}{3E_e} \right)$$

$$\langle r \rangle_{(2)} = \int r d^3r \int d^3s \rho_w(|\vec{r} - \vec{s}|) \rho_{ch}(s)$$

-First moment of convoluted weak and charge densities
= 1st Zemach moment

The weak magnetism correction

Interference between the transverse (magnetic) distribution of the vector current and the spin distribution of the axial current.

$$J_V^\mu = [Q_V, \vec{J}_C + \vec{J}_V^{MEC}]$$

Affects GT transitions

$$J_A^\mu = [Q_A + Q_A^{MEC}, \vec{\Sigma}]$$

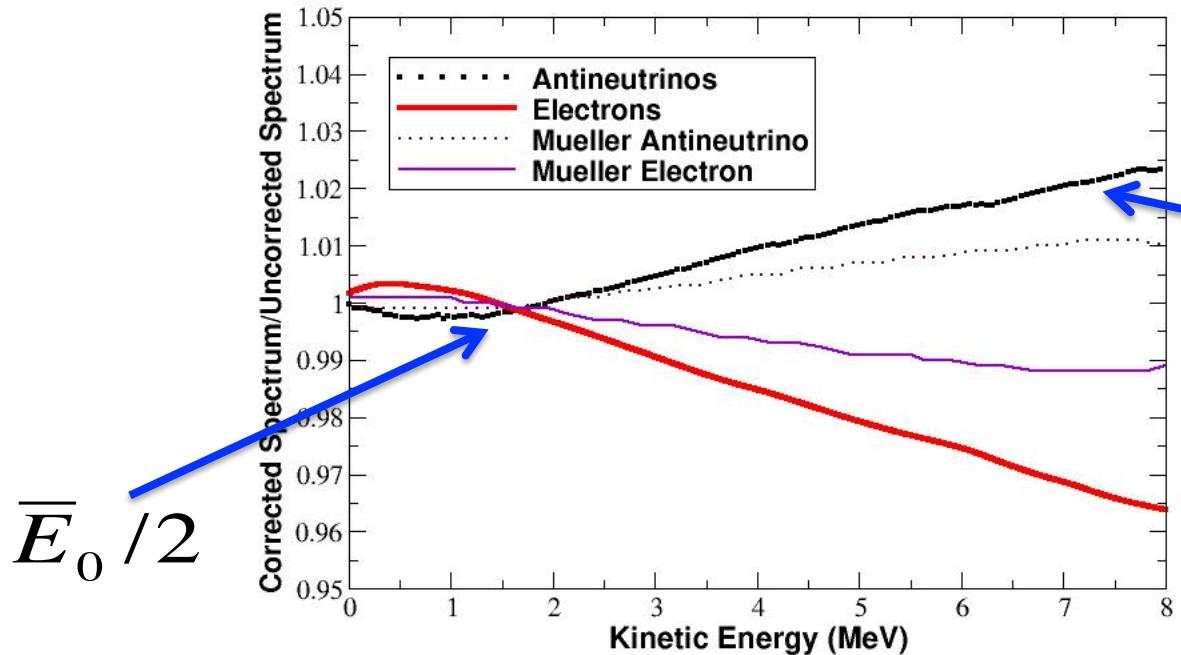
Equivalent correction for spin-flip component of forbidden transitions

The correction is operator dependent:

$$\delta_{WM}^{GT} = \frac{4(\mu_V - \frac{1}{2})}{6M_N g_A} (E_e \beta^2 - E_v)$$

$$\delta_{WM}^{unique1st} = \frac{3(\mu_V - \frac{1}{2})}{5M_N g_A} \left[\frac{(p_e^2 + p_v^2)(p_e^2/E_e - E_v) + \frac{2}{3} \frac{p_e^2 E_v (E_v - E_e)}{E_e}}{(p_e^2 + p_v^2)} \right]$$

If all transitions are treated as allowed GT, the corrections lead to the anomaly — the ν_e spectrum is shifted to higher energy



$$\approx \frac{1}{2} \left[\frac{4(\mu_\nu - \frac{1}{2})}{6M_n g_A} - \frac{3Z\alpha R}{2\hbar c} \right]$$

- Obtain larger effect & stronger energy dependence than Mueller because the form of our corrections are different
- Linear increase in the number of antineutrinos with $E_n > 2$ MeV

Without detailed nuclear structure information there is no method of determining which operators determine the forbidden transitions

$$S(E_e, Z, A) = \frac{G_F^2}{2\pi^3} p_e E_e (E_0 - E_e)^2 C(E) F(E_e, Z, A) (1 + \delta(E_e, Z, A))$$

Classification	ΔJ^π	Operator	Shape Factor $C(E)$	Fractional Weak Magnetism Correction $\delta_{WM}(E)$
Allowed GT	1^+	$\Sigma \equiv \sigma\tau$	1	$\frac{2}{3} \left[\frac{\mu_\nu - 1/2}{M_N g_A} \right] (E_e \beta^2 - E_\nu)$
Non-unique 1 st Forbidden GT	0^-	$[\Sigma, r]^{0-}$	$p_e^2 + E_\nu^2 + 2\beta^2 E_\nu E_e$	0
Non-unique 1 st Forbidden ρ_A	0^-	$[\Sigma, r]^{0-}$	λE_0^2	0
Non-unique 1 st Forbidden GT	1^-	$[\Sigma, r]^{1-}$	$p_e^2 + E_\nu^2 - \frac{4}{3}\beta^2 E_\nu E_e$	$\frac{3}{5} \left[\frac{\mu_\nu - 1/2}{M_N g_A} \right] \left[\frac{(p_e^2 + E_\nu^2)(\beta^2 E_e - E_\nu) + 2\beta^2 E_e E_\nu (E_\nu - E_e)/3}{(p_e^2 + E_\nu^2 - 4\beta^2 E_\nu E_e)/3} \right]$
Unique 1 st Forbidden GT	2^-	$[\Sigma, r]^{2-}$	$p_e^2 + E_\nu^2$	$\frac{3}{5} \left[\frac{\mu_\nu - 1/2}{M_N g_A} \right] \left[\frac{(p_e^2 + E_\nu^2)(\beta^2 E_e - E_\nu) + 2\beta^2 E_e E_\nu (E_\nu - E_e)/3}{(p_e^2 + E_\nu^2)} \right]$
Allowed F	0^+	τ	1	0
Non-unique 1 st Forbidden F	1^-	$r\tau$	$p_e^2 + E_\nu^2 + \frac{2}{3}\beta^2 E_\nu E_e$	0
Non-unique 1 st Forbidden \vec{J}_V	1^-	$r\tau$	E_0^2	-

Table lists the 6 1-body operators that enter 1st forbidden transitions

Have not derived a similar table for the Finite Size corrections

$$\vec{k} \cdot \vec{r} = \frac{(\vec{p}_e + \vec{p}_\nu) \cdot \vec{r}}{\hbar c}$$

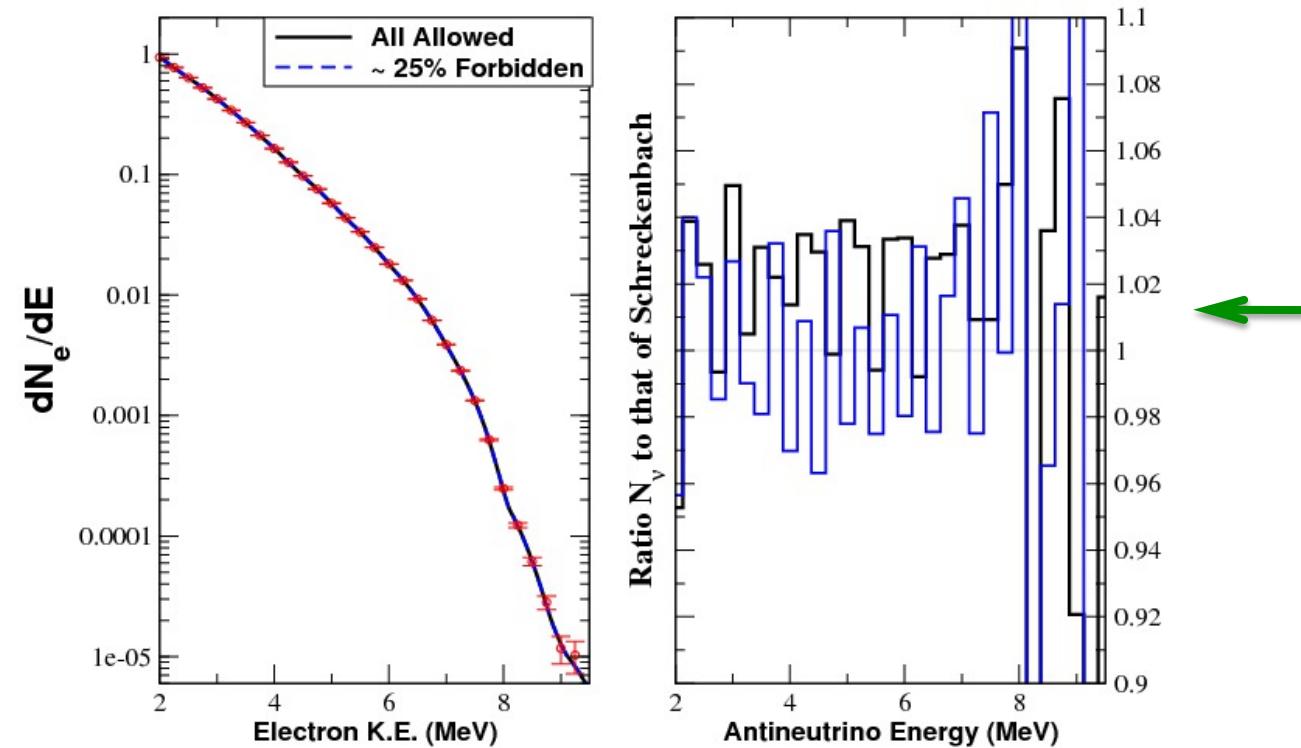
The uncertainty in how to treat the forbidden transitions introduces an uncertainty in the antineutrino flux

- No way to determine what combination of operators and hence corrections to use for this ($\sim 25\%$) component of the spectra
- No clear way to estimate the uncertainty due the non-unique forbidden transitions
- Therefore, we examined the uncertainties using several prescriptions.

For different choices of the forbidden operators we examined:

- » 1. Inferred antineutrino spectrum from a fit to the beta spectrum
- » 2. Changes in $k(E_e, E_\nu) = N_\nu(E_\nu)/N_\beta(E_e)$
- » 3. Changes in $R \equiv \sum_i \left[\frac{\partial N_\nu(E_\nu)}{\partial a_i} \right] / \left[\frac{\partial N_\beta(E_e)}{\partial a_i} \right]$
- » 4. Change in the predicted antineutrino spectra

1a. Fit to Schreckenbach's beta spectrum



All allowed:
=> +2.2% more e^+ detected

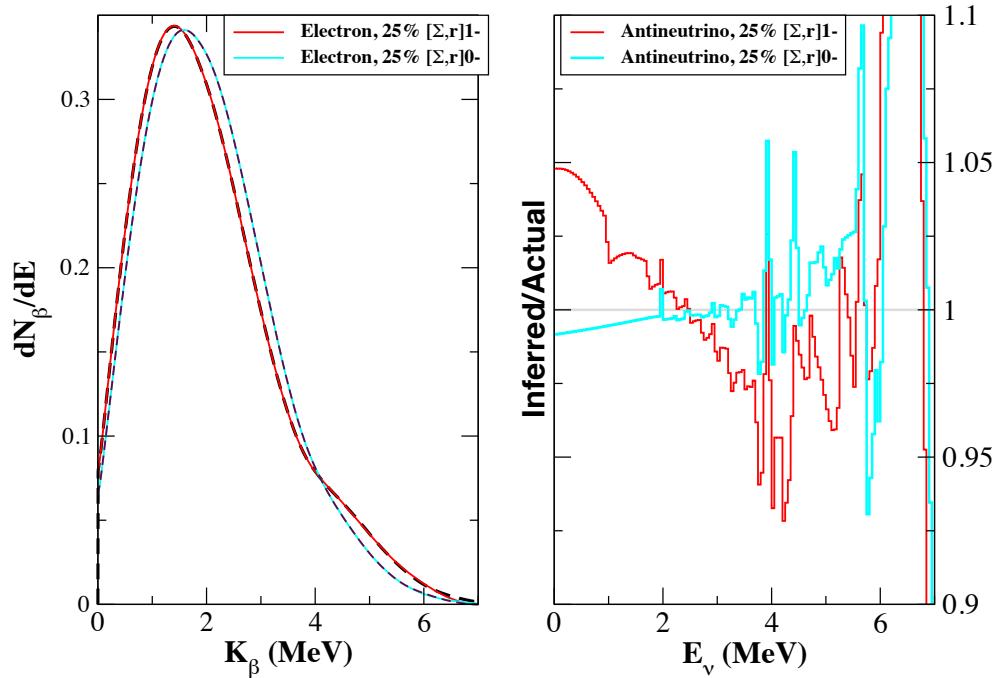
25% forbidden transition
=> only +0.06% more e^+ but
~4% change in spectrum

Different fitting procedures: (1) all allowed; (2)all branches either allowed or forbidden; (3) 30% forbidden equally spaced ;(4) 30% forbidden with a bias to higher energies + several different combinations of forbidden operators

Changes in the antineutrino spectrum range from 0-4%

Problem arises because of lack of knowledge on how to treat forbidden transitions

1b. Examine the inferred antineutrino spectrum from a fitted β -spectrum for fictitious nucleus with 4 - 50 branches



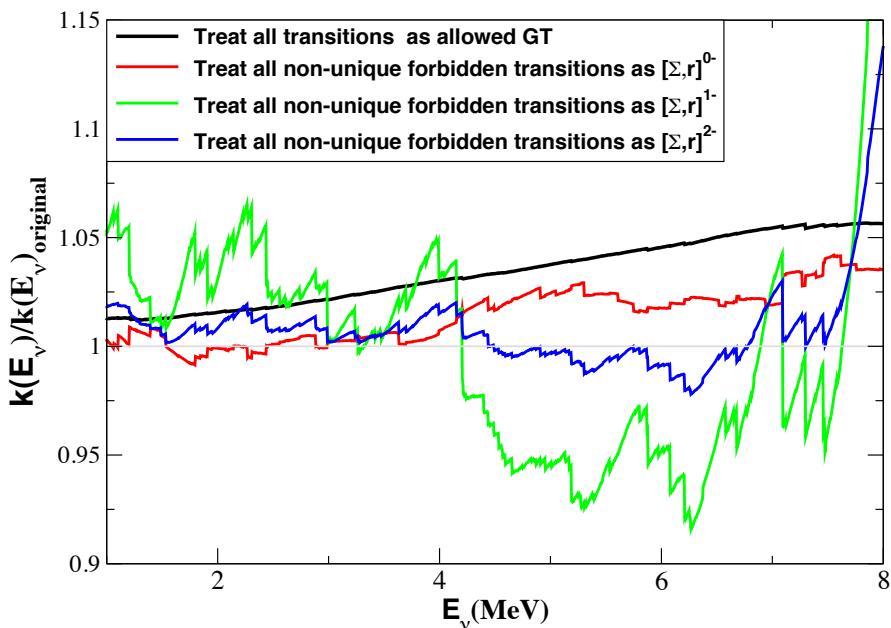
- Actual spectrum involves 30% forbidden transitions and 70% allowed GT
- Fit assumes 100% allowed GT transition
- Inferred $\bar{\nu}_e$ spectrum deviates from the actual $\bar{\nu}_e$ spectrum by $\sim 5\%$
 - very similar results found for 4, 10 and 50 branches

The differences arise from assuming that forbidden transitions can be ignored

2. Examine the bi-varient function $k(E_e, E_\nu) = N_\nu(E_\nu)/N_\beta(E_e)$

If $k(E_e, E_\nu)$ changes by a small percentage for some path in the (E_e, E_ν) plane as we change the operators that determine the forbidden transitions

=> A prescription for inferring $N_\nu(E_\nu)$ from known $N_e(E_e)$



Found no path in the (E_n, E_e) plane that left the function $k(E_n, E_e)$ unchanged by 5%

=> Uncertainty in $N_\nu(E_\nu)$ is ~5%

3. Examine change in the antineutrino spectrum with respect to the β -spectrum

Examine the function R :

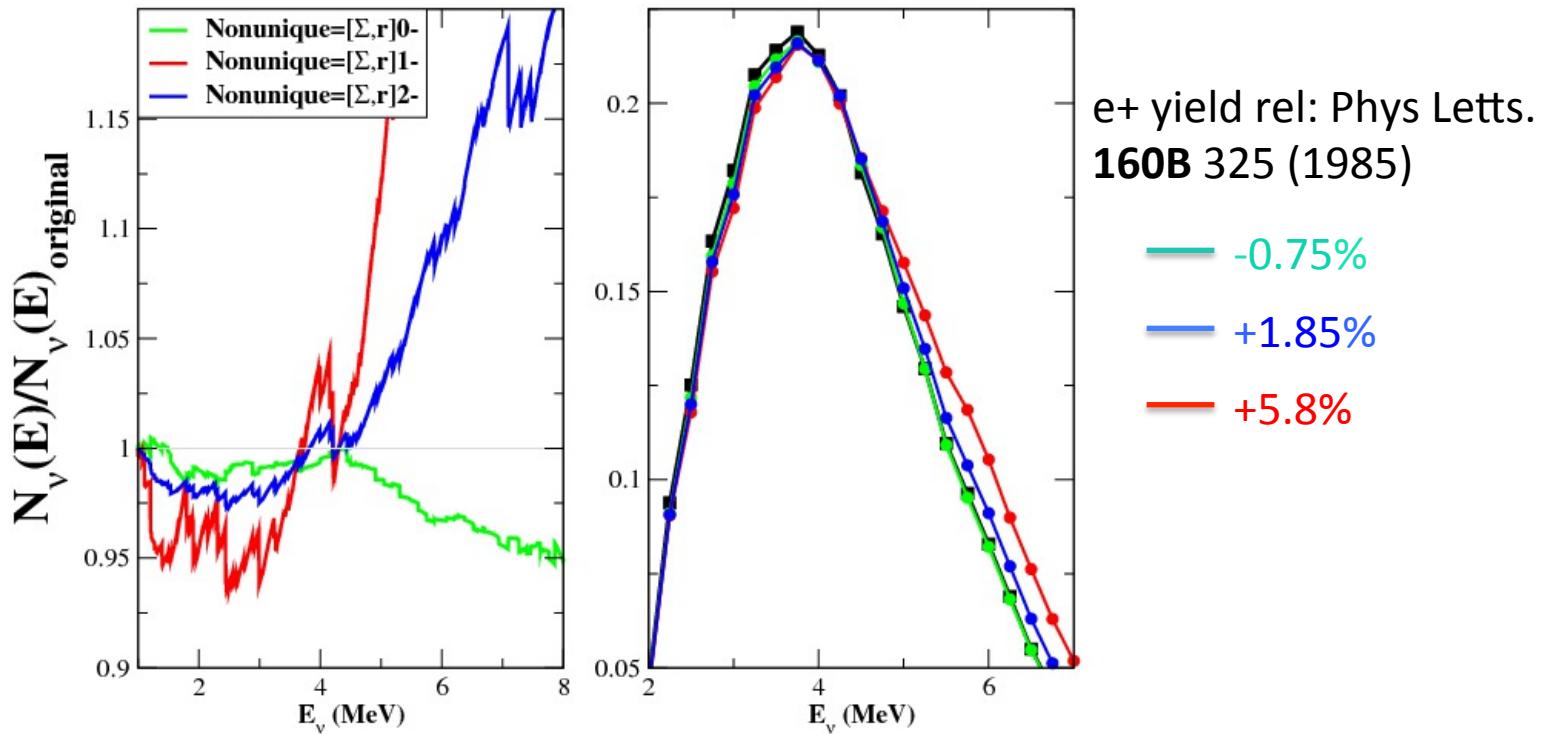
$$R \equiv \sum_i \left\lfloor \frac{\partial N_\nu(E_\nu)}{\partial a_i} \right\rfloor / \left\lfloor \frac{\partial N_\beta(E_\beta)}{\partial a_i} \right\rfloor,$$

$$N_\nu(E_\nu) = \sum_i a_i S(E_\nu, E_{0i}) ; \quad N_\beta(E_\beta) = \sum_i a_i S(E_\beta, E_{0i})$$

As we changed the operators determining the forbidden transitions there was no path in the (E_e, E_ν) plane such that R changed by as little as 5%

=> Uncertainty in $N_\nu(E_\nu)$ is ~5%

4. Examine the ratio of antineutrino spectra for different treatments of the forbidden transitions



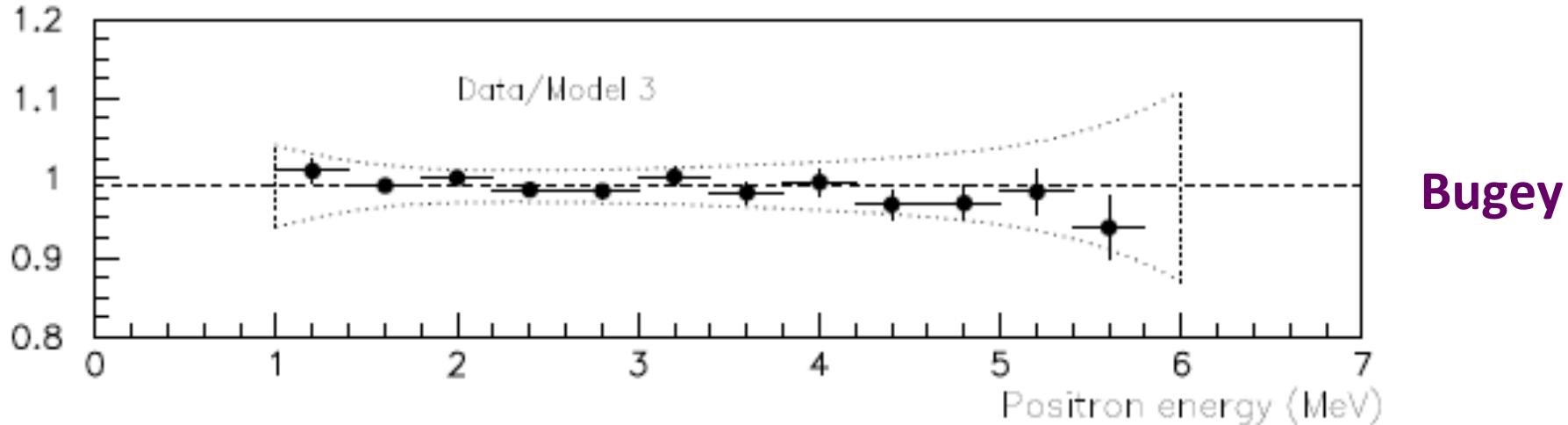
Ratio of antineutrino spectrum to the original ILL spectrum allowing different operators to dominate the non-unique forbidden transitions

The forbidden transitions introduce an operator-dependent distortion of spectrum
A purely theoretical analysis is unlikely to reduce the uncertainties in a model-independent way

=> Need direct measurement of the shape of the spectrum to reduce the uncertainties

What does experiment say?

Bugey 3 did not report any significant distortions



Do Double Chooz, Daya Bay, Reno see distortions in the near detectors?

Weak Magnetism Correction- Allowed Transition

For free neutron

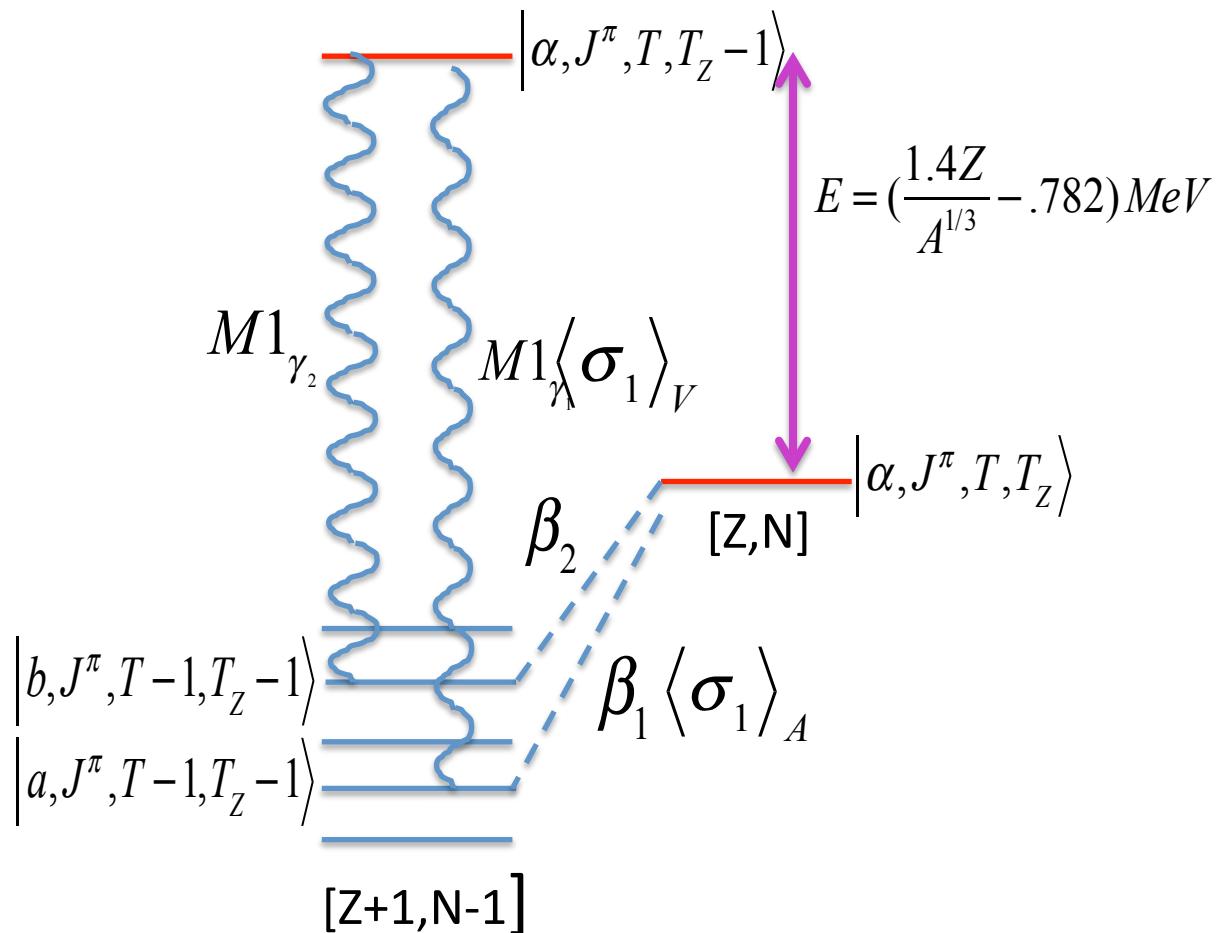
$$ft = \frac{6140}{G_A^2 \langle \sigma \rangle^2} = 1270$$

$$\log ft = 3.1$$

For Log ft=6

$$\langle \sigma \rangle^2 = 3.8 \cdot 10^{-3}$$

$\langle \vec{l} \rangle$ contributions and
differing meson exchange
effects will modify the weak
magnetism correction.



Summary

- Weak magnetism and finite size corrections are the principal effects that led to the claimed anomaly
- These corrections increase the energy of antineutrino spectrum above ~ 2 MeV if all transitions are treated as allowed
- Forbidden transitions $\sim 30\%$ - tend to distort the shape of the neutrino spectrum. (Hopefully visible in near term experiments)
- Uncertainty in how to treat non-unique 1st forbidden transitions is the order of the size of the anomaly.
- The more probing evaluation of orbital and meson exchange effects on weak magnetism corrections is needed.
- **Anomaly certainly not ruled out**